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IN DEPTH

Protecting Cardiovascular Health From Wildfire Smoke

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ABSTRACT: Wildfire smoke is a rapidly growing threat to global cardiovascular health. We review the literature linking wildfire smoke exposures to cardiovascular effects. We find substantial evidence that short-term exposures are associated with key cardiovascular outcomes, including mortality, hospitalization, and acute coronary syndrome. Wildfire smoke exposures will continue to increase over the majority of Earth's surface. For example, the United States alone has experienced a 5-fold increase in annual area burned since 1972, with 82 million individuals estimated to be exposed to wildfire smoke by midcentury. The associated rise in excess morbidity and mortality constitutes a growing global public health crisis. Fortunately, the effect of wildfire smoke on cardiovascular health is modifiable at the individual and population levels through specific interventions. Health systems therefore have an opportunity to help safeguard patients from smoke exposures. We provide a roadmap of evidence-based interventions to reduce risk and protect cardiovascular health. Key interventions include preparing health systems for smoke events; identifying and educating vulnerable patients; reducing outdoor activities; creating cleaner air environments; using air filtration devices and personal respirators; and aggressive management of chronic diseases and traditional risk factors. Further research is needed to test the efficacy of interventions on reducing cardiovascular outcomes.

Key Words: air pollution ■ cardiovascular diseases ■ climate change ■ global health ■ smoke ■ wildfires

Unplanned landscape fires, or *wildfires*, are a threat to global cardiovascular health. Wildfire smoke is a key contributor to global fine particulate matter ($PM_{2.5}$; particulate matter air pollution [PM] <2.5 μm in diameter) air pollution, which is the leading environmental risk factor for cardiovascular disease (CVD).[1] $PM_{2.5}$ is responsible for an estimated 13.3% of all cardiovascular deaths globally (2.5 million), mainly through ischemic heart disease and stroke.[1] The $PM_{2.5}$ from global landscape fire smoke alone is associated with more than 675,000 deaths annually worldwide,[2] mostly with cardiovascular causes.

The threat of wildfire smoke to cardiovascular health is growing.[3–6] Since 2001, climate change, curtailing of prescribed burns, and the expanding wildland-urban interface have led to a 77% increase in the daily population exposure to wildfire smoke.[6] Notable recent fires have decimated wildlands across North America, Australia, and Brazil, with the United States experiencing a 5-fold increase in annual area burned since 1972.[7] Through midcentury, 82 million individuals living in the United States may be exposed to wildfire smoke.[8] Projections indicate that wildfires will increase in size, intensity, frequency, and duration over the majority of Earth's land surface.[9] Regions with the greatest increase in wildfire potential include the Amazon basin, sub-Saharan Africa, Central and Southern Asia, Australia, Central America, and the United States[10] (Figure 1). Smoke from these wildfires may be transported at hazardous concentrations for thousands of kilometers.[3] The associated rise in excess morbidity and mortality constitutes a growing public health crisis.

The effect of wildfire smoke on cardiovascular health is modifiable at the individual and population levels through specific interventions. Health systems therefore have an opportunity and a responsibility to help protect their patients from the harmful effects of wildfire smoke. In this article, we discuss the mechanisms by which wildfire smoke affects cardiovascular health and specific interventions clinicians and health systems can take to protect their patients. Our

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Nonstandard Abbreviations and Acronyms

CVD	cardiovascular disease
EPA	Environmental Protection Agency
HVAC	heating, ventilation, and air conditioning
PAC	portable air cleaner
PM	particulate matter air pollution
PM2.5	fine particulate matter

conclusions generally apply to other types of landscape fires, including land clearing fires and agricultural burning, which pose similar risks to cardiovascular health.

HEALTH EFFECTS OF WILDFIRES

Wildfires can affect cardiovascular health through several pathways (Figure 2). We focus primarily on the cardiovascular effects of smoke exposures, which are responsible for the greatest burden of attributable disease. Recent systematic reviews by Chen et al[11] and Reid et al[12] summarize the primary literature linking wildfire smoke exposure to subclinical cardiovascular effects. In addition, a growing literature links wildfire smoke to more severe outcomes such as cardiovascular mortality.[13] A wealth of studies also demonstrate cardiovascular outcomes associated with exposures to $PM_{2.5}$, the dominant pollutant in wildfire smoke.[14–16] The totality of evidence is sufficient to draw associations between wildfire smoke exposures and cardiovascular outcomes.[11,12,17]

Toxic Components of Wildfire Smoke

Wildfire smoke arises principally from incomplete combustion of cellulose, lignin, resins, waxes, sugars, and inorganic salts found in wood.[18] The result is a heterogeneous mixture of gaseous and particulate components, including particulate matter and a range of gaseous and semivolatile pollutants.[17,18] In addition, volatile organic compounds and NO_x react with sunlight to create the secondary pollutant ozone (O_3).[17,18] The exact composition and toxicity of emitted pollutants vary by type and moisture content of fuel, type, and temperature of fire (eg, flaming versus smoldering), landscape characteristics, rate of fuel consumption, and meteorological conditions.[5,11,17,19] If wildfires move into communities, additional chemicals from plastics and other anthropogenic materials will be released into the air.[20]

Of these toxic components, $PM_{2.5}$ has the largest body of evidence implicating adverse cardiovascular effects.[14–16] In 2010, the American Heart Association released a statement that reviewed hundreds of studies and concluded that the overall evidence is consistent with a causal relationship between $PM_{2.5}$ exposure and cardiovascular morbidity and mortality.[15] Recently, another American Heart Association statement concluded that PM from wildfires is associated with increased

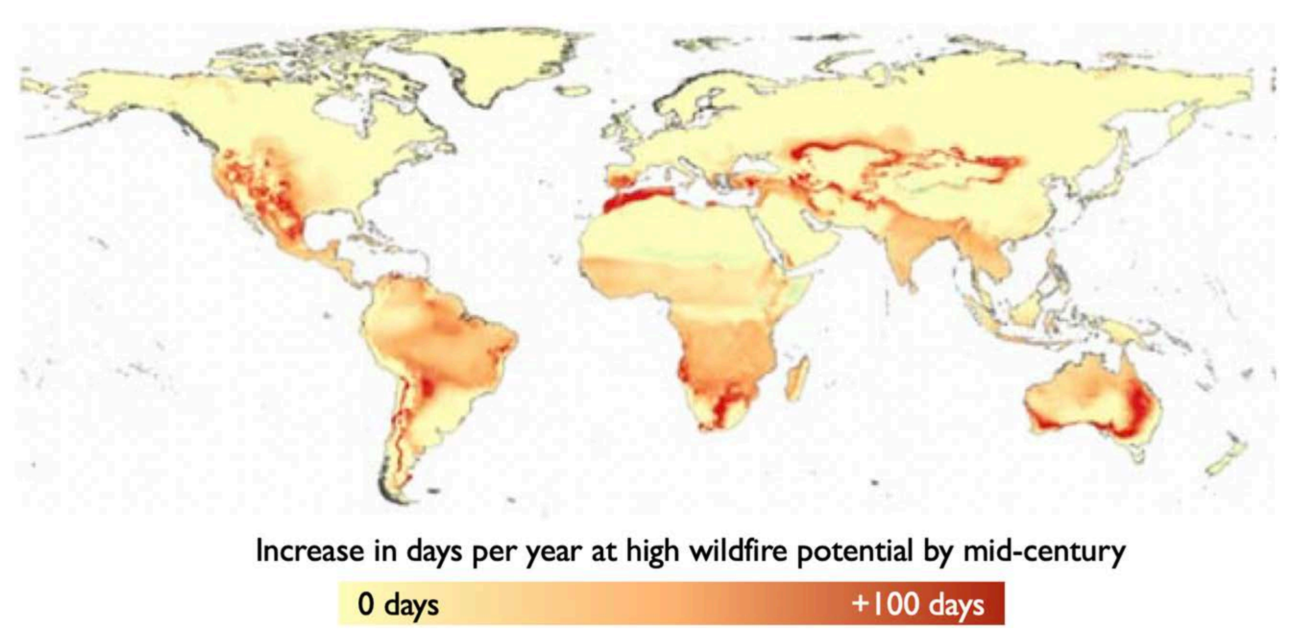

Figure 1. Predicted increase in days per year at high wildfire potential by midcentury.
Wildfire potential is estimated according to the Keetch-Byram Drought Index (KBDI), a widely used index of soil moisture deficit that incorporates estimates of temperature and precipitation.[10] The figure illustrates the predicted absolute change in days with a high KBDI for the years 2045 to 2055 compared with 1975 to 2005 under current estimates of climate change. Large regions of western North America, Central America, Australia, sub-Saharan Africa, Southern Asia, and the Amazon basin could experience an additional 2 months per year of high KBDI by midcentury. Adapted with permission from Gannon & Steinberg (2021).[10]

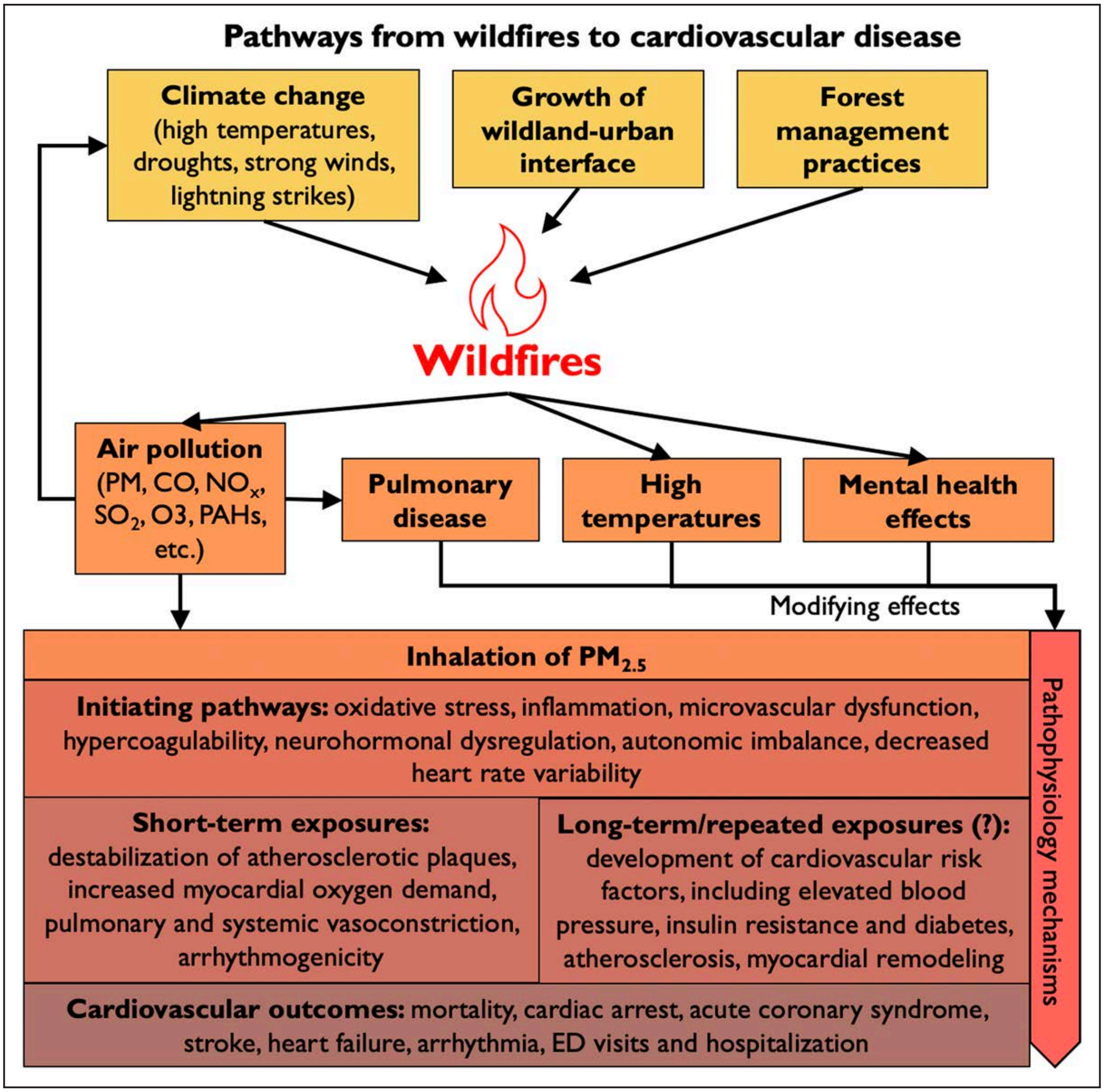

Figure 2. Pathophysiology of cardiovascular disease attributed to wildfires.
Environmental factors including climate change, forest management practices, and the growth of the wildland-urban interface have led to increased incidence and severity of wildfires. Smoke from wildfires contains hazardous pollutants that can trigger a cascade of cardiovascular effects resulting in adverse outcomes. These effects have been well-defined for short-term exposures, with further research needed for long-term or repeated exposures. Adverse outcomes may be amplified by pulmonary disease, mental health effects, and high temperatures. ED indicates emergency department; PAH, polycyclic aromatic hydrocarbon; PM, particulate matter air pollution; and PM2.5, fine particulate matter.

cardiovascular events with effect estimates comparable with those of ambient $PM_{2.5}$ from other sources.[16] $PM_{2.5}$ also serves as the best metric for smoke exposure during wildfire events because it is routinely measured, consistently elevated, and predictive of public health threats.[18,20] However, $PM_{2.5}$ serves as a proxy for the more complex wildfire smoke mixture; the potential role of other copollutants may also be relevant to health effects.

Timescales of Exposure

Most studies of wildfire smoke have examined the acute health effects of short-term exposures (hours to days). Findings are consistent with the broader literature on short-term exposures to $PM_{2.5}$ from other sources. Few studies have investigated the long-term health effects of repeated wildfire smoke exposures. Given the episodic nature of wildfires, it is problematic to extrapolate from studies of chronic urban $PM_{2.5}$ to wildfire smoke. Further studies on repeated wildfire exposures are urgently needed to estimate the cardiovascular effects.

Pathophysiology of Wildfire Smoke Exposure

Inhaled PM triggers initiating pathways that lead to the development of cardiovascular risk factors and outcomes (Figure 2). The biochemical pathways by which PM exposures lead to cardiovascular outcomes have been reviewed extensively elsewhere.[14,15,21–25] Here we review recent studies investigating the health effects of wildfire smoke specifically.

Initiating Pathways

Studies and reviews of ambient PM pollution have elucidated numerous harmful *initiating pathways*.[15,16,22,24] Inhaled PM deposits in the alveoli, damages local structures, and leads to a cascade of oxidative stress, activation of inflammatory cells, impaired microvascular function, platelet activation, hypercoagulability, and decreased heart rate variability.[15,16,22] These effects may be modified by host susceptibility (eg, individuals with proinflammatory conditions) or the presence of copollutants (eg, ozone inactivates native antioxidant defenses).

Studies specifically of wildfire smoke and woodsmoke have observed similar effects.[11,12] In humans, controlled clinical exposure studies with woodsmoke have demonstrated impaired microvascular function, elevated central arterial stiffness, decreased heart rate variability, elevated markers of oxidative stress and hypercoagulability (eg, fibrinogen, IL-1β, and TNF-α), and cell cycle disruption and cytotoxicity.[11,12] In vivo animal studies show that wildfire-derived PM exposure is associated with higher oxidative stress, inflammatory cell lines, cytokine release, and antioxidant depletion.[11,12] In vitro studies also have shown that exposure to wildfire- or woodsmoke-derived PM is associated with higher inflammatory responses, reactive oxygen species, cell death, DNA fragmentation, and reduced antioxidant levels.[11,12,18]

Development of Cardiovascular Risk Factors

Elevated Blood Pressure

The initiating pathways of impaired vasodilation, elevated arterial stiffness, endothelial dysfunction, and autonomic dysfunction all lead to elevations in blood pressure. Controlled-exposure studies consistently demonstrate a linear relationship between ambient $PM_{2.5}$ exposure and blood pressure elevations.[21,22] The existing literature on $PM_{2.5}$ from wildfire smoke and woodsmoke exposures provides a consistent picture.[11] Ambient exposures to $PM_{2.5}$ from forest and peat fires have been associated with short-term elevations in blood pressure.[26] Similarly, controlled clinical exposure studies with woodsmoke in humans have demonstrated associations with higher blood pressure.[27]

Atherosclerosis

Ambient air pollution has been associated with coronary and carotid atherosclerosis. Proposed mechanisms include vascular inflammation, macrophage infiltration, and accumulation of oxidized lipids.[15,21,22] In addition, $PM_{2.5}$ exposure has been associated with the development of more vulnerable atherosclerotic plaques.[28] Early studies on woodsmoke exposure are consistent with these findings.[11] Cohort studies of burning biomass fuel indoors have shown association with higher carotid intima media thickness and prevalence of carotid plaques.[29] In addition, murine and in vitro studies have found that gaseous components of woodsmoke (eg, SO_2, NH_4, NO_x, and CO) are important in this proatherosclerotic response.[11]

Destabilization of vulnerable atherosclerotic plaques is a key mechanism by which short-term exposures to wildfire smoke may lead to acute cardiovascular events, including stroke or acute coronary syndrome.[21,22] This may occur in individuals with known atherosclerotic disease or reveal previously subclinical atherosclerosis. Because these acute effects require an underlying vulnerability, individuals without atherosclerotic plaques are unlikely to experience such outcomes from short-term smoke exposures.

Other Effects

Ambient air pollution exposures have been associated with the development of dyslipidemia, insulin resistance, diabetes, gestational diabetes, and obesity,[22] which are major risk factors for atherosclerotic CVD. In addition, these exposures have been associated with left ventricular hypertrophy, diastolic dysfunction, and myocardial fibrosis, which are risk factors for heart failure.[21,22] These effects are associated more strongly with chronic ambient air pollution exposures and have not been studied specifically in human populations exposed to wildfire smoke.

Modifying Effects

Several additional mechanisms modify the relationship between wildfire smoke exposures and cardiovascular outcomes (Figure 2).

Heat Effects

Wildfires often coincide with warm weather. Elevated ambient temperatures are associated with higher rates of cardiovascular outcomes. A recent study of 652 cities found that the association between $PM_{2.5}$ and cardiovascular mortality was stronger in areas with higher annual mean temperatures.[30] Similarly, a 1°C increase in temperature has been associated with a 3.4% rise in cardiovascular mortality.[31] Smoke exposures interact with high temperatures to worsen cardiovascular outcomes.[32] For example, a study of a wildfire event near Moscow found that interactions between high temperatures and air pollution from wildfires contributed to cardiovascular deaths in excess of an additive effect.[33]

Mental Illness

Exposure to $PM_{2.5}$ is associated with anxiety and depression after controlling for socioeconomic factors.[34] In addition, qualitative studies have documented the disruptive effects of wildfires, including evacuations, school relocations, business closures, property loss, reduced outdoor and physical activity, food insecurity, and stress and uncertainty.[35] Individuals thus affected are at higher risk for mental illness, including posttraumatic stress disorder, anxiety, depression, and insomnia.[35,36]

This mental illness may persist for years after wildfire exposures, particularly among children and adolescents.[37] Depression and anxiety are known predictors of accelerated atherosclerotic CVD.[38]

Pulmonary Disease

Pulmonary disease exacerbations may precipitate cardiovascular outcomes by decreasing blood oxygenation or increasing right ventricular afterload. Epidemiological studies demonstrate that wildfire smoke exposure is associated with both acute and chronic respiratory illness, including pneumonia, lung cancer, asthma exacerbation, chronic obstructive pulmonary disease exacerbation, impaired gas exchange, and higher respiratory hospital admissions.[4,12,18,19,39] In addition, wildfire smoke appears to be associated with higher risk of death from COVID-19.[40]

Community Disruptions

Like other natural disasters, wildfires disrupt communities in ways that may have important consequences on cardiovascular health. For example, individuals may experience displacement from home, disrupted diet and exercise, interruption of social networks, and limited access to health care.[35,41,42] A full review of these disruptions is beyond the scope of this article. Further research into these issues is warranted, especially to compare wildfires with other emergency and humanitarian situations such as hurricanes, earthquakes, military actions, and pandemic surges.

Cardiovascular Outcomes

The American Heart Association and European Society of Cardiology recognize $PM_{2.5}$ as a modifiable risk factor for cardiovascular outcomes.[14,15] Key cardiovascular outcomes attributed to $PM_{2.5}$ include cardiovascular mortality, acute coronary syndrome, stroke, heart failure, and arrhythmias.[14,15,21,24] A recent American Heart Association Scientific Statement estimated that the risk of these outcomes increases by 1% to 2% for short-term exposures and 5% to 10% for long-term exposures per 10 µg/m^3 of $PM_{2.5}$.[16] Cardiovascular outcomes have been observed for both low-concentration and high-concentration exposures.[21,24] Moreover, observational studies have found that lower ambient $PM_{2.5}$ exposures are associated with reductions in cardiovascular risk.[43]

$PM_{2.5}$ is the pollutant most consistently elevated in wildfire smoke.[18] A growing literature supports the claim that $PM_{2.5}$ from wildfires is at least as hazardous to cardiovascular health as $PM_{2.5}$ from other sources.[13] A clear majority of studies demonstrate an association, although challenges inherent in studies of wildfire exposures may have led some epidemiologic studies to report null associations (see Future Directions).[11–13] Current expert opinion is that the existing body of evidence on wildfire smoke supports an association with cardiovascular outcomes.[11,12] Even if the risk of cardiovascular outcomes attributed to smoke exposures may be low for a single individual, widespread exposures that affect large populations result in a significant burden of disease.[22] We summarize this literature below.

Cardiovascular Mortality

Numerous large prospective cohort studies have corroborated the relationship between ambient $PM_{2.5}$ and cardiovascular mortality.[14,15,22,24,30] Looking specifically at wildfire smoke, a recent review identified 10 epidemiologic studies that have examined associations between cardiovascular mortality and short-term wildfire smoke exposures.[11] Of these, 8 demonstrated significant positive associations, with varying magnitude of association.[11] For example, a recent meta-analysis of data from 10 cities in Southern Europe demonstrated that 5-day cardiovascular mortality was higher by 6.3% (95% CI, 1.0 to 11.9) for days when PM <10 µm in diameter from forest fires exceeded 8 µg/m^3, compared with days when PM <10 µm in diameter from forest fires was <8 µg/m^3.[44] The largest time series study on the effect of wildfire $PM_{2.5}$ exposures included 15 million cardiovascular deaths from 749 cities across 43 countries from 2000 to 2016. Using a random-effects meta-analysis, the authors found the relative risk of cardiovascular mortality was higher by 1.9% (95% CI, 1.3 to 2.5) per each 10 µg/m^3 increase in the 3-day moving of $PM_{2.5}$. Studies have also identified associations between wildfire smoke exposures and all-cause mortality.[13]

Cardiovascular Hospitalization

Large epidemiologic studies have demonstrated that exposure to ambient air pollutants such as PM and NO_2, even at levels below current guidelines, are associated with higher risk of cardiovascular hospitalization.[14–16,24] There are substantial data specifically on wildfire smoke exposures,[19] with most studies showing an association between smoke exposures and emergency department visits for cardiovascular complaints,[11,45] outpatient cardiovascular visits,[46] hospital cardiovascular admissions,[47,48] and intensive care unit admissions.[39] The association appears particularly robust for elderly individuals.[11,12,17,45] For example, a large study of hospitalizations in 692 US counties within 200 km of 123 wildfires found significantly higher cardiovascular hospitalizations associated with elevated $PM_{2.5}$ exposure, regardless of whether the $PM_{2.5}$ came from wildfires or another source.[49] A recent time-series analysis of 148 million hospital admissions across Brazil from 2000 to 2015 found that cardiovascular hospital admissions in the day after exposure were higher by 1.1% (95% CI, 0.8 to 1.4) per 10 µg/m^3 increase in wildfire-related $PM_{2.5}$.[47] A separate meta-analysis found that smoky days were associated with a 5.5% elevated risk of hospitalization for ischemic heart disease, although the CI crossed the null (95% CI, 0.8 to 10.1).[50] Severe wildfire events may result in hospi-

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tals exceeding capacity: a recent study projected that a simulated severe 7-day wildfire smoke event (120 μg/m^3) would raise local intensive care unit admissions by 131%.[39]

Cardiac Arrest

Some case-crossover studies have identified associations between out-of-hospital cardiac arrest and exposure to ambient PM and ozone pollution.[51,52] Air pollution exposures also have been associated with ventricular tachyarrhythmias, particularly in individuals with previous myocardial infarction and left ventricular dysfunction.[53] Looking specifically at wildfire smoke exposures, out-of-hospital cardiac arrest has been associated with heavy smoke during the California wildfires of 2015 to 2017[54] as well as with elevated $PM_{2.5}$ levels during the Australian wildfires of 2006 to 2007.[52,55]

Acute Coronary Syndrome

Many controlled studies have identified associations between air pollution exposure and incident fatal or nonfatal myocardial infarction, with the strongest associations seen for ST-segment–elevation myocardial infarction in individuals with pre-existing coronary artery disease.[14,15,22] Looking specifically at wildfire smoke, exposure to $PM_{2.5}$ from wildfires has been strongly associated with acute myocardial infarction in elderly individuals,[56] as well as with emergency department visits[45] and hospitalizations[55] for acute myocardial infarction.

Stroke

Cohort studies, time series, and meta-analyses have found associations between air pollution exposures and stroke, both ischemic and hemorrhagic.[21] Studies specific to wildfires have also demonstrated a significant association between smoke exposure and stroke[48] or emergency department visits for cerebrovascular issues.[45]

Heart Failure

Air pollution exposures may accelerate ventricular remodeling and heart failure, resulting in a higher risk of heart failure hospitalization or death.[57] In addition, a recent retrospective study of 21 800 patients with heart transplant suggests that exposure to $PM_{2.5}$ is associated with higher mortality among this subpopulation.[58] Looking specifically at woodsmoke, exposure to $PM_{2.5}$ from wood-burning furnaces has been associated with a higher risk of hospitalization for heart failure in Australia.[59]

PROTECTING PATIENTS AND COMMUNITIES

Wildfire smoke threatens cardiovascular health, and reductions in $PM_{2.5}$ exposures are associated with improved health outcomes.[16] This presents an important public health opportunity to improve cardiovascular health by mitigating wildfire smoke exposures. In what follows, we discuss key actions for clinicians and their patients, as well as health systems and their communities (Figure 3).

Risk Assessment

Highly exposed individuals and susceptible individuals are 2 groups that are at higher risk of cardiovascular events (Figure 4). Highly exposed individuals are those exposed to high concentrations or durations of wildfire smoke. Susceptible individuals are those with a higher risk of a cardiovascular event for a given concentration of wildfire smoke exposure.

Identifying High Exposure

Smoke level forecasts are publicly available (Table). For example, the US Environmental Protection Agency (EPA) offers the Air Quality Index which provides real-time short-term $PM_{2.5}$ exposure estimates with colored thresholds to clarify levels of risk.[60] The AirNow wildfire page provides detailed information on air quality conditions affected by wildfires. Forecasts for future smoke conditions are also available.[61,62]

Disparities may exist for wildfire smoke exposures, with disproportionate exposures falling on Indigenous peoples, tribal populations, the elderly, and communities of low socioeconomic status.[70,71] These groups also may have lower baseline health status and fewer resources to reduce their exposures or manage any health effects.[20,70] Other highly exposed groups include individuals spending significant time outdoors, including children, athletes, agricultural workers, landscapers, construction crews, first responders, firefighters, etc.[12,20]

Identifying Susceptibility

Epidemiologic studies have identified groups with greater susceptibility to cardiovascular events attributed to wildfire smoke exposure, including individuals with pre-existing CVD; older adults (>65 years); women; Indigenous peoples; Black individuals; and low socioeconomic status individuals.[11,17,20,46,55] By triggering cardiovascular events, smoke exposure may also unmask individuals with previously unknown CVD. The presence of multiple susceptible characteristics likely increases risk, although the exact interactions between risk factors require further investigation.

Deciding Whether to Intervene

Global and national organizations have produced guidelines for intervening at different thresholds of exposure. The World Health Organization recommends that average daily $PM_{2.5}$ exposures not exceed 15 μg/m^3 and average annual $PM_{2.5}$ exposures not exceed 5 μg/m^3.[72] Currently, however, there is no evidence base to guide implementation of interventions at specific exposure cutoffs. Moreover, there appears to be no lower concentration of $PM_{2.5}$ exposure that can be considered safe;[18,22]

	Preparations for wildfire season	Reducing smoke exposures and effects
Individuals	• Educate on health risks of wildfire smoke and strategies to reduce exposure • Connect to air quality monitoring and alert systems • Prepare clean air space at home • Stockpile key supplies for prolonged indoor periods (e.g., medications, food, hygienic supplies) • Reduce smoke susceptibility with heart healthy lifestyle and cardioprotective medications	• Follow air quality monitoring and alert systems • Reduce time outdoors • Create and use a clean air space at home • Prioritize clean air facilities (e.g., gyms, not outdoors) • Employ air filtration (e.g., PACs, HVAC filtration, high-efficiency automobile cabin filters) • Wear well-fitted personal respirators • Consider temporary relocation if highly susceptible
Health Systems	• Name an interdisciplinary team to develop a *wildfire smoke preparedness plan* and manage health system response • Educate clinicians on the health effects of wildfire smoke and evidence-based interventions to reduce exposures • Identify high risk patients based on susceptibility and local wildfire smoke forecasts • Optimize HVAC systems accordingly • Aggressive primary and secondary prevention of CVD	• Create clean air spaces in hospitals and clinics and monitor indoor $PM_{2.5}$ concentrations • Provide alerts and recommendations to patients at risk • Participate in clinical trials testing the efficacy of interventions (e.g., air filtration, personal respirators) • Advocate for resources and policies to prevent wildfires • Monitor and evaluate programs and apply lessons to the following wildfire season • Provide mental health services to affected individuals
Communities	• Develop a *wildfire smoke preparedness plan* involving leadership from key agencies involved in clean air, disaster response, health care, and public messaging • Identify high risk communities based on social vulnerability and wildfire smoke forecasts • Stockpile key supplies (e.g., personal respirators)	• Provide community clean air shelters • Deliver PSAs regarding hazardous exposures and risk mitigation strategies • Supply adequate firefighting resources and personnel • Support improved forest management practices • Participate in efforts to reduce climate change

Figure 3. Summary of approach to protecting cardiovascular health from wildfire smoke.
Communities, health systems, and individuals in high-risk areas may take action indicated to prepare for wildfire season and reduce harmful smoke exposures. CVD indicates cardiovascular disease; HVAC, heating, ventilation, and air conditioning; PAC, portable air cleaner; $PM_{2.5}$, fine particulate matter; and PSA, public service announcement.

as soon as there is smoke, there is risk for susceptible populations within the first hours of exposure.[11,12,55] Therefore, the best approach is probably intervening to keep exposures As Low As is Reasonably Achievable (ALARA). During smoke events, all affected individuals—and particularly susceptible individuals—should have access to the following interventions to minimize exposures and associated cardiovascular events.

Interventions to Protect Cardiovascular Health

We propose the following interventions to reduce smoke exposure, particularly for patients and communities at elevated risk of cardiovascular events. These interventions should be tailored to the individual or community and considered essential preparations for wildfire season (Figure 3). Implementation should account for personal factors that may encumber changes in patient behavior, including lack of capability, opportunity, or motivation.[73]

Patient Education

Many individuals with CVD are unfamiliar with the harmful effects of air pollution or hold misconceptions (eg, "smoke is 'natural' so it can't be harmful").[18] Such individuals are more likely to modify their behavior on the basis of messages they receive from clinicians.[5] Clinicians therefore have a responsibility to educate susceptible patients about the risks of smoke exposure, as well as specific interventions to mitigate harm.[5] Clinicians in smoke prone areas can direct patients to educational materials (Table).[20]

Standard Primary and Secondary Prevention

Individuals with pre-existing CVD are far more likely to develop cardiac events in the setting of wildfire smoke exposures. Clinicians can reduce susceptibility by aggressive management of traditional risk factors, including hypertension, diabetes, and atherosclerotic disease.[15,21] In smoke-prone areas, medical therapy should be optimized annually *before* the start of fire season.

Cleaner Indoor Air at Home

Every exposed home should prioritize cleaner indoor air. As much as 65% of exposure to outdoor air particles occurs while indoors.[74] Protecting a single room is often easier and less expensive than protecting an entire house or apartment. Individuals should choose a room(s) where they spend significant time (eg, bedroom) with few windows or doors.[20] Keeping indoor air clean is best achieved by the following steps.

Seal the Building Envelope

The building envelope should be sealed to reduce the infiltration of outdoor air and to facilitate indoor air

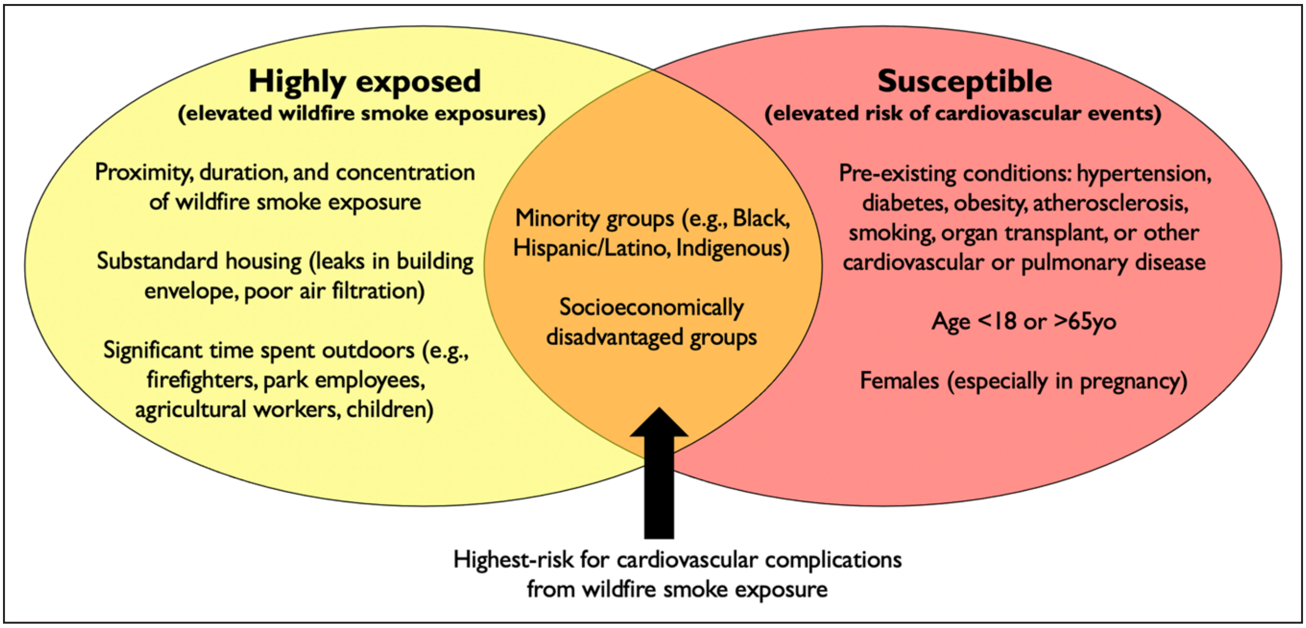

Figure 4. Risk assessment: factors determining exposure and susceptibility.
Highly exposed individuals are exposed to higher concentrations of wildfire smoke. Susceptible individuals are at elevated risk of cardiovascular complications for any given level of wildfire smoke exposure. Individuals at highest risk are both highly exposed and susceptible. Clinicians can screen for these factors to identify patients at elevated risk, for whom interventions to reduce exposures may be warranted.

cleaning.[75] Doors and windows should be kept closed.[20] In addition, any *indoor* sources of air pollution should be discontinued (eg, smoking, incense, solid fuel–burning stoves and furnaces, dry sweeping or vacuuming).[20]

Central Air

Some heating, ventilation, and air conditioning (HVAC) or mechanical ventilation systems can be fitted with high-efficiency filters, which remove the majority of $PM_{2.5}$ from incoming or recirculated indoor air.[16,20,69,76] When using HVAC air filtration, it is important to use the most efficient in-duct particle filter that conforms to the specific systems in place (Minimum Efficiency Reporting Value 13 or higher is best).[69] Filters should fit snugly and be replaced when soiled. Initial studies affirm that this may translate into a cardiovascular benefit: analyses of cardiovascular hospitalizations in the United States found that air conditioning significantly modifies the relationship between PM exposure and cardiovascular hospitalization.[77]

Portable Air Cleaners

In homes without effective central air filtration, portable air cleaners (PACs) are one of the most protective technologies available for reducing wildfire smoke exposure.[78] Carefully controlled studies have demonstrated that PACs with high-efficiency particulate air (HEPA) filters can remove the majority of indoor $PM_{2.5}$,[16,75,76] with significant reductions in average individual exposures. For example, a recent study reported that PACs reduced $PM_{2.5}$ from wildfires by 73% during working hours in an active office setting.[79] Such reductions in exposure appear to translate into cardiovascular benefit. A recent meta-analysis of 10 randomized blinded controlled trials demonstrated that PAC use was associated with a lower systolic blood pressure by an average of 3.9 mm Hg (95% CI, 7.0 to 0.9).[80] A modeling study estimated that if PACs were adopted widely across the United States, the subsequent reduction in PM exposure from various sources would prevent approximately 64 000 premature deaths annually.[74] Several considerations are needed for a PAC to be effective. The PAC must be used for the volume of space it is designed for, typically an average room sealed off from outdoor air.[16,76] Additional information is available from the EPA[68] and other groups[81] (Table).

Be Mindful of Competing Risks

Individuals must be mindful of the competing risk of high temperatures (eg, heat stroke) that may occur with decreased ventilation or air conditioning.[16,30] Maintenance of comfortable indoor temperatures should not be compromised for enhanced smoke reduction, because the immediate health risks for extreme heat are generally larger than those related to smoke. If an individual cannot create a cleaner room with appropriate temperature regulation, then they should seek daytime relief in community cleaner air shelters (see below).[20] In addition, individuals remaining indoors should be mindful of the competing risk of transmission of infectious diseases, such as COVID-19.

Cleaner Air Shelters

Some residential buildings do not protect against penetrating smoke, particularly among disadvantaged communities and in low- and middle-income countries.[17,20] The EPA recommends opening community cleaner air

Table. Online Resources for Clinicians and Patients

Online resource	Contents
Estimating exposures	
EPA AirNow Fire and Smoke Map[60]	Current $PM_{2.5}$ exposure estimates
Forest Service BlueSky Program[61]	Near-term forecasts of $PM_{2.5}$ levels (<1 week)
Interagency Fire Center Outlooks[62]	Extended forecasts (weeks to months)
European Commission Copernicus[63]	Global fire and smoke estimates
Alert systems	
EPA AirNow EnviroFlash forecasts[64]	Air quality alerts by text or email
EPA AirNow smartphone application[65]	Real-time air quality estimates, forecasts, and alerts
Protecting patients and communities	
EPA Wildfire Smoke Guide for Public Health Officials[20]	Guide to health effects, interventions to reduce exposure, and tips for communicating with the public
EPA Smoke-Ready Toolbox for Wildfires[66]	Links to information about smoke and health, preventive measures, smoke maps, and state advisories
EPA Particulate Pollution and Your Patients' Health[67]	Course for clinicians on $PM_{2.5}$ and health effects, with clinical scenarios and patient education materials
EPA Wildfires and Indoor Air Quality[68]	Recommendations for patients during wildfire events
ASHRAE Protecting Commercial Building Occupants from Smoke[69]	Recommended HVAC measures to improve indoor air for hospitals, clinics, and other commercial buildings

This table lists the key resources for estimating smoke exposures, providing alerts to patients, and measures to protect cardiovascular health. ASHRAE indicates American Society of Heating, Refrigerating, and Air-Conditioning Engineers; EPA, Environmental Protection Agency; HVAC, heating, ventilation, and air conditioning; and $PM_{2.5}$, fine particulate matter.

facilities for these groups at $PM_{2.5}$ concentrations >35.5 μg/m^3. Health care systems can partner with local governmental and nongovernmental organizations to provide cleaner air shelters for such individuals. Shelters can provide a temporary respite from smoke, or potentially provide housing until severe smoke abates. Possible locations include hotels, hospitals, schools, libraries, malls, sports facilities, and senior centers.[20]

Cleaner Indoor Air in Health Facilities

Hospitals, clinics, and long-term care facilities should strive to become clean air facilities. This often requires strategies different from those used in homes or other buildings.

Optimize Central Air Filtration

Health facilities have complex filtration and ventilation systems, and intake of outdoor air may be required for these systems to work.[20,69] As a result, hospitals and clinics need individualized approaches. Managers should consult with HVAC specialists before wildfire season to test baseline indoor air quality and determine how best to limit smoke intake while maintaining positive indoor pressure and essential ventilation services.[70] Guidance for hospitals and clinics to attain cleaner air during wildfires is provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers.[69,82]

Reduce Outdoor Air Infiltration

The building envelope should be inspected for leaks.[75] Points of entry and exit should be restricted as much as possible, prioritizing double doors with vestibules. Signage should be placed throughout the facility to remind individuals to keep windows and doors closed.[69] Outdoor air dampers should seal tightly when closed.[69] Filter edges must be tightly sealed around ventilation systems.[69] In addition, indoor sources of air pollution should be reduced or directly ventilated, if possible (eg, laboratory equipment).

Monitoring

Health facilities should continuously monitor and compare outdoor and indoor PM concentrations to assess the effectiveness of cleaner air interventions.[83] Changes in indoor pollutant concentrations can signal building managers to adjust HVAC systems and other interventions.

Create Designated Cleaner Air Spaces

Facilities unable to provide cleaner air throughout the building should create clearly designated and monitored cleaner air spaces. PACs can be used to improve air quality in these areas.

Facemasks

During wildfire events, susceptible individuals should consider wearing a personal respirator as a supplement to cleaner indoor air.[20] Particle respirators can effectively reduce $PM_{2.5}$ exposures if they are well-fitted to the wearer. There are many types of particle respirators available (eg, N95, CAN95, KF94, etc), all offering similar protection despite being tested by different standards. Although a fitted particle respirator is preferred, a well-fitting 3-layer cloth or disposable surgical mask can also provide moderate protection.[84] Simple 1-layer cloth masks, bandanas, scarves, T-shirts, or other face coverings provide essentially no protection.[20]

Studies demonstrate that wearing a particle respirator in environments with elevated ambient $PM_{2.5}$ levels may improve surrogate markers of cardiovascular risk.[16,85] For example, a case-crossover trial in Beijing enrolled 98 patients with coronary artery disease who performed a scripted walk with and without an N95 respirator. Use of an N95 was associated with significant reductions in blood pressure, maximal ST-segment depression, and higher heart rate variability.[85]

Minimize Outdoor Activities

Individuals should be instructed to reduce time outdoors during elevated wildfire smoke exposures.[16] Wildfire pollution levels often follow a diurnal cycle based on local wind, weather, and topography.[20] Individuals can monitor these trends and relegate essential outdoor activities or errands to lulls in exposure. Errands can also be reduced by stocking up on nonperishable food, sanitary supplies, prescription medications, and other essentials *before* wildfire season.

The long-term health benefits of routine exercise have been observed in large epidemiological studies to outweigh the risks of chronically high ambient pollution levels.[16] However, the risk-benefit ratio of exercising during short-term wildfire smoke exposures specifically has not been studied. For healthy individuals choosing to exercise outdoors, the EPA recommends limiting outdoor physical activity at $PM_{2.5}$ levels above 55.5 μg/m^3, and ceasing outdoor physical activity at levels above 150.5 μg/m^3 or during periods of heavy smoke.[20] Healthy individuals should also avoid high-intensity or prolonged exercise during smoke events.[14,15,21,22] Those with pre-existing CVD should avoid all outdoor exercise during polluted conditions.[16] As an alternative, individuals should pursue exercise in a clean air environment (eg, gym with central air filtration).

Automobile Modifications

Individuals can take precautions while driving to reduce their exposure to wildfire smoke.[86] Closing windows and using cabin air filters lowers in-cabin $PM_{2.5}$ levels and has been shown to reduce markers of oxidative stress.[87] In addition, turning on air conditioning and "recirculate" mode has been associated with improved heart rate variability.[88] High-risk individuals who spend significant time driving also may consider installing high-efficiency cabin filters, which are more effective than standard filters at reducing $PM_{2.5}$ levels.[89] Prolonged operation of air conditioning on recirculation mode can lead to buildup of high levels of exhaled carbon dioxide, which can be a safety concern; briefly opening windows every 15 minutes will minimize this potential.[86]

Air Quality Monitoring, Forecasting, and Response Plans

Before the start of wildfire season, patients should be connected to services providing forecasts and alerts about hazardous smoke levels in their vicinity. Patients can use this information to guide response plans and behavior modifications (eg, when to stay indoors, use air filtration, wear a respirator). Individuals who follow behavioral recommendations from Air Quality Indexes can successfully lower their individual exposure,[90] although it remains unclear whether these indices reduce cardiovascular outcomes.

Forecasting services are available to estimate smoke exposures for the coming days and months (Table).[61–63,91] Local air quality indices (eg, EPA AirNow Wildfire Map[60]) provide real-time estimates of local pollution levels. Local smoke advisories can provide alerts by phone or email. For example, the EnviroFlash and BlueSky websites provide daily air quality forecasts and alerts from local agencies.[61,92] Smartphone applications (eg, SmokeSense, AirNow, AirRater) can provide users with real-time air quality estimates and customized alerts.[65,93,94]

Clinicians should be aware of sensors purchased for individual use. Although individual monitoring devices hold the promise of providing personalized estimates not possible from modeled estimates,[16] questions remain about accuracy, precision, cost, and reliability under different meteorological conditions.[17,20,75] Various low-cost sensor networks may provide more reliable local exposure estimates.[95]

Health care providers may wish to develop their own alert system for susceptible patients. Exposure maps could be integrated into electronic medical records to provide clinicians with exposure forecasts at the patients' home addresses.[96] Alerts can be sent by phone, email, social media, or medical record services (eg, MyChart), or posted on the provider's website. The US Centers for Disease Control and Prevention provides additional guidance on how to use social media for health messaging.[97]

Preparing Health Systems for Wildfire Season

With the threat of wildfires increasing globally, the number of affected health systems will continue to grow.[9] Health systems can assess their risk using the forecasting tools discussed above (Table).[62,91] Systems at risk should make preparations for wildfire season (Figure 3) to protect their susceptible patients and avoid shortfalls in beds, supplies, human resources, and key partnerships.[69,75]

Wildfire Leadership Team

Health systems should designate an interdisciplinary team to make preparations for wildfire season. Key responsibilities of this team include educating the health workforce; drafting public messaging; ensuring clean indoor air for system facilities; determining a source for exposure estimates; developing partnerships with clean air agencies; securing supplies for at-risk populations (eg, respirators, PACs); and advocating for policies to protect the local community.

Educating Clinicians

Clinicians should receive some training on the risks of wildfire smoke exposure, as well as specific interventions and resources to recommend to patients. The EPA's "Wildfire Smoke Guide for Public Health Officials" provides many useful resources.[20] Clinicians can participate in a related online training course, "Particulate Pollution and Your Patients' Health," for which they can received continuing education credits.[67] Last, medical education and training should include the pathophysiology and air pollution–attributable diseases.[21–23]

Broader Policy Considerations

As leaders in their communities, health care systems can provide a strong voice for political action. Building codes can be modified to require indoor air filtration, sealing of building envelopes, and cleaner air spaces.[21] Resources are needed to finance firefighting efforts and prescribed burns of underbrush overgrowth that can prevent larger fires.[5] Occupational standards are needed to protect outdoor workers (eg, agricultural workers), such as the standards adopted by California in 2019.[20] In addition, regulations and penalties can reduce agricultural burning, tropical rainforest burning, and accidental ignitions along the wildland-urban interface.[98] Investments in air pollution control typically bring economic benefits through decreased health care costs and the increased productivity of healthier populations.[25] In the United States, for example, every dollar invested in air pollution control has yielded an estimated return of $30.[99]

FUTURE DIRECTIONS

More research is needed to delineate the relationships between wildfire smoke exposures, cardiovascular outcomes, and the efficacy of targeted interventions. Research endeavors will benefit from an interdisciplinary approach, combining expertise in clinical care, toxicology, physiology, epidemiology, exposure modeling, forestry, environmental studies, economics, social science, and public policy.[19] Federal agencies can develop a comprehensive national research program combining varied expertise to evaluate and reduce the risks of wildfire smoke.[5] Research centers can be located in affected regions and house mobile teams to implement research action plans on unpredictable fire events.[5] Key research questions include the exposure-response relationship and trials of targeted interventions. More research dollars are needed to support these efforts.

Exposure-Response Relationship

More data are needed on the effects of long-term or repeated exposures to wildfire smoke, and whether such exposures cause or accelerate atherosclerotic CVD. Studies are needed to determine whether periods of clean air between wildfire smoke exposures may facilitate physiologic recovery. The exposure-response relationship also must be defined for susceptible groups (eg, those with pre-existing CVD or genetic predispositions), for highly exposed groups (eg, outdoor workers), for different life stages (eg, pregnant women and the elderly), and for different sources and components of wildfire smoke.[5] Toxicology research and observational studies can determine how the composition, toxicity, and health effects of wildfire smoke differ from other sources of $PM_{2.5}$.[5] Studies are needed to determine "how clean is clean enough," that is, what level of reduction is necessary to achieve a cardiovascular benefit at the individual and population level.[100] This information is critical to guide decisions on exactly when, how, and for whom to intervene. Last, studies are needed to understand potential extracardiac effects of wildfire smoke, including neuroinflammation and neurodegenerative diseases, pulmonary diseases, preterm birth, and malignancy.[25]

Forecasting Tools

Current long-term forecasting platforms predict wildfire potential on the basis of recent meteorological data (eg, National Interagency Fire Center Outlooks[62]). However, these platforms do not provide long-term forecasts for smoke exposure specifically. Improved forecasting tools are needed to estimate smoke exposures for the coming season. Historical data on smoke exposures can be used to identify high-risk areas,[96] although this approach requires prospective validation. These forecasts could be integrated with data on social vulnerability to identify areas at highest risk.

Trials of Targeted Interventions

Larger randomized trials are needed to evaluate the efficacy of interventions to reduce smoke exposures and health outcomes. Although some trials have evaluated the effect of interventions on surrogate markers of cardiovascular health, future trials are needed to assess the effect on cardiovascular outcomes.[16]

Trials may investigate both individual- and community-level interventions. Key individual interventions to be tested include behavioral modifications; personal respirators (eg, N95s); portable air cleaners; central air filtration; and cardioprotective medications. A recent expert workshop concluded that indoor PACs with high-efficiency particulate air filtration were the most favorable technology to adopt for clinical trials for $PM_{2.5}$ reductions.[76] Key community interventions to be tested include alert/advisory messaging systems; cleaner air shelters; and enhanced firefighting and forest management practices.

Trials should assess how the efficacy of the intervention varies with different parameters, including baseline pollution levels; total reductions observed for different copollutants ($PM_{2.5}$, O_3, NO_2, etc); and efficacy in susceptible subgroups (eg, pre-existing CVD). Careful data should be collected about air pollution components and the fraction attributable to wildfire smoke versus fossil fuel emissions or other sources. Studies should involve minority communities and low- and middle-income countries, which are underrepresented in the existing literature and likely to suffer the greatest growth in wildfires this century.[11] To ensure scalability of interventions, studies should also collect data on cost-effectiveness and assess effects on other social and structural determinants of health.

The fact that wildfires often are unpredictable and short-lived is a key limitation to implementing prospective randomized trials. It may be difficult to secure ethical review board approval and enroll a sufficient number of participants for an appropriately powered prospective trial.[11] Difficulties with enrollment leading to low case counts and wide CIs likely contribute to the presence of null associations in the literature.[3,11,12] Other causes of null studies likely include no accounting for cumulative smoke exposures; exposure misclassification because of dependence on air quality monitoring stations or satellite imagery; and actual differences in toxicity of smoke from different fires.[11] To overcome these challenges, investigators may target more highly exposed and susceptible groups, intervening in regions with the highest exposure levels and high-risk patient populations. In addition, packages combining multiple interventions may provide a stronger effect size, and the use of composite end points may increase event rates. Initial studies may need to start with a surrogate end point such as blood pressure reductions, which is well-validated as an end point because it leads to proportionate reductions in cardiovascular events.[76]

CONCLUSIONS

Wildfires have become increasingly common and severe and will continue to worsen for the foreseeable future, posing a grave threat to global cardiovascular health. Wildfire smoke exposures are quantifiable and modifiable at the individual level. Clinicians and provider organizations therefore have an opportunity and a responsibility to help mitigate these exposures in their service populations. We provide a set of evidence-based interventions for patients and communities to protect cardiovascular health.

ARTICLE INFORMATION

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REFERENCES

1. Murray CJ, Aravkin AY, Zheng P, Abbafati C, Abbas KM, Abbasi-Kangevari M, Abd-Allah F, Abdelalim A, Abdollahi M, Abdollahpour I. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet.* 2020;396:1223–1249. doi: 10.1016/S0140-6736(20)30752-2
2. Roberts G, Wooster M. Global impact of landscape fire emissions on surface level PM2. 5 concentrations, air quality exposure and population mortality. *Atmos Environ.* 2021;252:118210. doi: 10.1016/j.atmosenv.2021.118210
3. Xu R, Yu P, Abramson MJ, Johnston FH, Samet JM, Bell ML, Haines A, Ebi KL, Li S, Guo Y. Wildfires, global climate change, and human health. *N Engl J Med.* 2020;383:2173–2181. doi: 10.1056/nejmsr2028985
4. Neumann JE, Amend M, Anenberg S, Kinney PL, Sarofim M, Martinich J, Lukens J, Xu J-W, Roman H. Estimating PM2. 5-related premature mortality and morbidity associated with future wildfire emissions in the western US. *Environ Res Lett.* 2021;16:035019. doi: 10.1088/1748-9326/abe82b
5. Rice MB, Henderson SB, Lambert AA, Cromar KR, Hall JA, Cascio WE, Smith PG, Marsh BJ, Coefield S, Balmes JR. Respiratory impacts of wildland fire smoke: future challenges and policy opportunities. an official American Thoracic Society Workshop Report. *Ann Amer Thorac Soc.* 2021;18:921–930. doi: 10.1513/AnnalsATS.202102-148ST
6. Watts N, Amann M, Arnell N, Ayeb-Karlsson S, Belesova K, Boykoff M, Byass P, Cai W, Campbell-Lendrum D, Capstick S The 2019 report of The Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate. *Lancet.* 2019;394:1836–1878. doi: 10.1016/S0140-6736(19)32596-6
7. Williams AP, Abatzoglou JT, Gershunov A, Guzman-Morales J, Bishop DA, Balch JK, Lettenmaier DP. Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future.* 2019;7:892–910. doi: 10.1029/2019EF001210
8. Liu JC, Mickley LJ, Sulprizio MP, Dominici F, Yue X, Ebisu K, Anderson GB, Khan RF, Bravo MA, Bell ML. Particulate air pollution from wildfires in the Western US under climate change. *Clim Change.* 2016;138:655–666. doi: 10.1007/s10584-016-1762-6
9. Bowman DM, Kolden CA, Abatzoglou JT, Johnston FH, van der Werf GR, Flannigan M. Vegetation fires in the Anthropocene. *Nat Rev Earth Environ.* 2020;1:500–515. doi: 10.1038/s43017-020-0085-3
10. Gannon CS, Steinberg NC. A global assessment of wildfire potential under climate change utilizing Keetch-Byram drought index and land cover classifications. *Environ Res Commun.* 2021;3:035002. doi: 10.1088/2515-7620/abd836
11. Chen H, Samet JM, Bromberg PA, Tong H. Cardiovascular health impacts of wildfire smoke exposure. *Part Fibre Toxicol.* 2021;18:1–22. doi: 10.1186/s12989-020-00394-8
12. Reid CE, Brauer M, Johnston FH, Jerrett M, Balmes JR, Elliott CT. Critical review of health impacts of wildfire smoke exposure. *Environ Health Perspect.* 2016;124:1334–1343. doi: 10.1289/ehp.1409277
13. Chen G, Guo Y, Yue X, Tong S, Gasparrini A, Bell ML, Armstrong B, Schwartz J, Jaakkola JJ, Zanobetti A. Mortality risk attributable to wildfire-related PM2· 5 pollution: a global time series study in 749 locations. *Lancet Planetary Health.* 2021;5:e579–e587. doi: 10.1016/S2542-5196(21)00200-X
14. Newby DE, Mannucci PM, Tell GS, Baccarelli AA, Brook RD, Donaldson K, Forastiere F, Franchini M, Franco OH, Graham I, et al; ESC Working Group on Thrombosis, European Association for Cardiovascular Prevention and Rehabilitation. Expert position paper on air pollution and cardiovascular disease. *Eur Heart J.* 2015;36:83–93b. doi: 10.1093/eurheartj/ehu458
15. Brook RD, Rajagopalan S, PopeBrook CAJR, Bhatnagar A, Diez-Roux AV, Holguin F, Hong Y, Luepker RV, Mittleman MA, Peters A, et al; American Heart Association Council on Epidemiology and Prevention, Council on the Kidney in Cardiovascular Disease, and Council on Nutrition, Physical Activity and Metabolism. Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circulation.* 2010;121:2331–2378. doi: 10.1161/CIR.0b013e3181dbece1
16. Rajagopalan S, Brauer M, Bhatnagar A, Bhatt DL, Brook JR, Huang W, Münzel T, Newby D, Siegel J, Brook RD. Personal-level protective actions against particulate matter air pollution exposure: A scientific statement from the American Heart Association. *Circulation.* 2020;142:e411–e431. doi: 10.1161/CIR.0000000000000931
17. Cascio WE. Wildland fire smoke and human health. *Sci Total Environ.* 2018;624:586–595. doi: 10.1016/j.scitotenv.2017.12.086
18. Naeher LP, Brauer M, Lipsett M, Zelikoff JT, Simpson CD, Koenig JQ, Smith KR. Woodsmoke health effects: a review. *Inhal Toxicol.* 2007;19:67–106. doi: 10.1080/08958370600985875
19. Black C, Tesfaigzi Y, Bassein JA, Miller LA. Wildfire smoke exposure and human health: Significant gaps in research for a growing public health issue. *Environ Toxicol Pharmacol.* 2017;55:186–195. doi: 10.1016/j.etap.2017.08.022
20. Stone SL, Sacks J, Lahm P, Clune A, Quinn T, D'Alessanndro M, Radonovich L, Hutson M, Mirabelli M. Wildfire Smoke: a Guide for Public Health Officials.

Environmental Protection Agency (2021). Accessed June 8, 2021. https://www.airnow.gov/publications/wildfire-smoke-guide/wildfire-smoke-a-guide-for-public-health-officials/
21. Al-Kindi SG, Brook RD, Biswal S, Rajagopalan S. Environmental determinants of cardiovascular disease: lessons learned from air pollution. *Nat Rev Cardiol.* 2020;17:656–672. doi: 10.1038/s41569-020-0371-2
22. Rajagopalan S, Al-Kindi SG, Brook RD. Air pollution and cardiovascular disease: JACC state-of-the-art review. *J Am Coll Cardiol.* 2018;72:2054–2070. doi: 10.1016/j.jacc.2018.07.099
23. Hadley MB, Baumgartner, J, Vedanthan R. Developing a clinical approach to air pollution and cardiovascular health. *Circulation* 2018;137:725–742. doi: 10.1161/CIRCULATIONAHA.117.030377
24. Rajagopalan S, Landrigan PJ. Pollution and the heart. *N Engl J Med.* 2021;385:1881–1892. doi: 10.1056/nejmra2030281
25. Landrigan PJ, Fuller R, Acosta NJR, Adeyi O, Arnold R, Basu NN, Balde AB, Bertollini R, Bose-O'Reilly S, Boufford JI, et al. The Lancet Commission on pollution and health. *Lancet.* 2017;391:462–512. doi: 10.1016/S0140-6736(17)32345-0
26. Tinling MA, West JJ, Cascio WE, Kilaru V, Rappold AG. Repeating cardiopulmonary health effects in rural North Carolina population during a second large peat wildfire. *Environ Health.* 2016;15:1–12. doi: 10.1186/s12940-016-0093-4
27. Fedak KM, Good N, Walker ES, Balmes J, Brook RD, Clark ML, Cole-Hunter T, Devlin R, L'Orange C, Luckasen G. Acute effects on blood pressure following controlled exposure to cookstove air pollution in the STOVES Study. *JAMA.* 2019;8:e012246. doi: 10.1161/JAHA.119.012246
28. Sun Q, Wang A, Jin X, Natanzon A, Duquaine D, Brook RD, Aguinaldo J-GS, Fayad ZA, Fuster V, Lippmann M. Long-term air pollution exposure and acceleration of atherosclerosis and vascular inflammation in an animal model. *JAMA.* 2005;294:3003–3010. doi: 10.1001/jama.294.23.3003
29. Painschab MS, Davila-Roman VG, Gilman RH, Vasquez-Villar AD, Pollard SL, Wise RA, Miranda JJ, Checkley W, Group CCS. Chronic exposure to biomass fuel is associated with increased carotid artery intima-media thickness and a higher prevalence of atherosclerotic plaque. *Heart.* 2013;99:984–991. doi: 10.1136/heartjnl-2012-303440
30. Liu C, Chen R, Sera F, Vicedo-Cabrera AM, Guo Y, Tong S, Coelho MS, Saldiva PH, Lavigne E, Matus P. Ambient particulate air pollution and daily mortality in 652 cities. *N Engl J Med.* 2019;381:705–715. doi: 10.1056/NEJMoa1817364
31. Bunker A, Wildenhain J, Vandenbergh A, Henschke N, Rocklöv J, Hajat S, Sauerborn R. Effects of air temperature on climate-sensitive mortality and morbidity outcomes in the elderly; a systematic review and meta-analysis of epidemiological evidence. *EBioMedicine.* 2016;6:258–268. doi: 10.1016/j.ebiom.2016.02.034
32. Hu X, Han W, Wang Y, Aunan K, Pan X, Huang J, Li G. Does air pollution modify temperature-related mortality? A systematic review and meta-analysis. *Environ Res.* 2022;210:112898. doi: 10.1016/j.envres.2022.112898
33. Shaposhnikov D, Revich B, Bellander T, Bedada GB, Bottai M, Kharkova T, Kvasha E, Lezina E, Lind T, Semutnikova E. Mortality related to air pollution with the Moscow heat wave and wildfire of 2010. *Epidemiology.* 2014;25:359. doi: 10.1097/EDE.0000000000000090
34. Pun VC MJ, Suh H. Association of ambient air pollution with depressive and anxiety symptoms in older adults: results from the NSHAP study. *Environ Health Perspect.* 2017;125:342–348. doi: 10.1289/EHP494
35. Eisenman DP, Kyaw MMT, Eclarino K. Review of the Mental Health Effects of Wildfire Smoke, Solastalgia, and Non-Traditional Firefighters. UCLA Center for Healthy Climate Solutions (2021). Accessed November 10, 2021. https://healthyclimatesolutions.org/wp-content/uploads/2021/07/REVIEW-OF-THE-MENTAL-HEALTH-EFFECTS-OF-WILDFIRE-SMOKE-SOLASTALGIA-AND-NON-TRADITIONAL-FIREFIGHTERS.pdf
36. Belleville G, Ouellet M-C, Morin CM. Post-traumatic stress among evacuees from the 2016 Fort McMurray wildfires: exploration of psychological and sleep symptoms three months after the evacuation. *Int J Environ Res Public Health.* 2019;16:1604. doi: 10.3390/ijerph16091604
37. Brown MR, Agyapong V, Greenshaw AJ, Cribben I, Brett-MacLean P, Drolet J, McDonald-Harker C, Omeje J, Mankowsi M, Noble S. After the Fort McMurray wildfire there are significant increases in mental health symptoms in grade 7–12 students compared to controls. *BMC Psychiatry.* 2019;19:1–11. doi: 10.1186/s12888-018-2007-1
38. Goldstein BI, Carnethon MR, Matthews KA, McIntyre RS, Miller GE, Raghuveer G, Stoney CM, Wasiak H, McCrindle BW. Major depressive disorder and bipolar disorder predispose youth to accelerated atherosclerosis and early cardiovascular disease: a scientific statement from the American Heart Association. *Circulation.* 2015;132:965–986. doi: 10.1161/CIR.0000000000000229
39. Sorensen C, House JA, O'Dell K, Brey SJ, Ford B, Pierce JR, Fischer EV, Lemery J, Crooks JL. Associations between wildfire-related PM2. 5 and intensive care unit admissions in the United States, 2006–2015. *GeoHealth.* 2021;5:e2021GH–e000385. doi: 10.1029/2021GH000385
40. Zhou X, Josey K, Kamareddine L, Caine MC, Liu T, Mickley LJ, Cooper M, Dominici F. Excess of COVID-19 cases and deaths due to fine particulate matter exposure during the 2020 wildfires in the United States. *Sci Adv.* 2021;7:eabi8789. doi: 10.1126/sciadv.abi8789
41. Babaie J. Cardiovascular diseases in natural disasters; a systematic review. *Arch Acad Emerg Med.* 2021;9. doi: 10.22037/aaem.v9i1.1208
42. Hayman KG, Sharma D, Wardlow RD, Singh S. Burden of cardiovascular morbidity and mortality following humanitarian emergencies: a systematic literature review. *Prehosp Disaster Med.* 2015;30:80–88. doi: 10.1017/S1049023X14001356
43. Laden F, Schwartz J, Speizer FE, Dockery DW. Reduction in fine particulate air pollution and mortality: extended follow-up of the Harvard Six Cities study. *Am J Respir Crit Care Med.* 2006;173:667–672. doi: 10.1164/rccm.200503-443OC
44. Faustini A, Alessandrini ER, Pey J, Perez N, Samoli E, Querol X, Cadum E, Perrino C, Ostro B, Ranzi A. Short-term effects of particulate matter on mortality during forest fires in Southern Europe: results of the MED-PARTICLES Project. *Occup Environ Med.* 2015;72:323–329. doi: 10.1136/oemed-2014-102459
45. Wettstein ZS, Hoshiko S, Fahimi J, Harrison RJ, Cascio WE, Rappold AG. Cardiovascular and cerebrovascular emergency department visits associated with wildfire smoke exposure in California in 2015. *J Am Heart Assoc.* 2018;7:e007492. doi: 10.1161/JAHA.117.007492
46. Johnston FH, Bailie RS, Pilotto LS, Hanigan IC. Ambient biomass smoke and cardio-respiratory hospital admissions in Darwin, Australia. *BMC Public Health.* 2007;7:1–8. doi: 10.1186/1471-2458-7-240
47. Ye T, Guo Y, Chen G, Yue X, Xu R, Coêlho MSZS, Saldiva PHN, Zhao Q, Li S. Risk and burden of hospital admissions associated with wildfire-related PM2· 5 in Brazil, 2000–15: a nationwide time-series study. *Lancet Planetary Health.* 2021;5:e599–e607. doi: 10.1016/S2542-5196(21)00173-X
48. Delfino RJ, Brummel S, Wu J, Stern H, Ostro B, Lipsett M, Winer A, Street DH, Zhang L, Tjoa T. The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003. *Occup Environ Med.* 2009;66:189–197. doi: 10.1136/oem.2008.041376
49. DeFlorio-Barker S, Crooks J, Reyes J, Rappold AG. Cardiopulmonary effects of fine particulate matter exposure among older adults, during wildfire and non-wildfire periods, in the United States 2008–2010. *Environ Health Perspect.* 2019;127:037006. doi: 10.1289/ehp3860
50. Karanasiou A, Alastuey A, Amato F, Renzi M, Stafoggia M, Tobias A, Reche C, Forastiere F, Gumy S, Mudu P. Short-term health effects from outdoor exposure to biomass burning emissions: a review. *Sci Total Environ.* 2021;146739 doi: 10.1016/j.scitotenv.2021.146739
51. Raza A, Bellander T, Bero-Bedada G, Dahlquist M, Hollenberg J, Jonsson M, Lind T, Rosenqvist M, Svensson L, Ljungman PL. Short-term effects of air pollution on out-of-hospital cardiac arrest in Stockholm. *Eur Heart J.* 2014;35:861–868. doi: 10.1093/eurheartj/eht489
52. Dennekamp M, Straney LD, Erbas B, Abramson MJ, Keywood M, Smith K, Sim MR, Glass DC, Del Monaco A, Haikerwal A. Forest fire smoke exposures and out-of-hospital cardiac arrests in Melbourne, Australia: a case-crossover study. *Environ Health Perspect.* 2015;123:959–964. doi: 10.1289/ehp.1408436
53. Folino F, Buja G, Zanotto G, Marras E, Allocca G, Vaccari D, Gasparini G, Bertaglia E, Zoppo F, Calzolari V. Association between air pollution and ventricular arrhythmias in high-risk patients (ARIA study): a multicentre longitudinal study. *Lancet Planetary Health.* 2017;1:e58–e64. doi: 10.1016/S2542-5196(17)30020-7
54. Jones CG, Rappold AG, Vargo J, Cascio WE, Kharrazi M, McNally B, Hoshiko S, Group CS. Out-of-hospital cardiac arrests and wildfire-related particulate matter during 2015–2017 California wildfires. *J Am Heart Assoc.* 2020;9:e014125. doi: 10.1161/JAHA.119.014125
55. Haikerwal A, Akram M, Del Monaco A, Smith K, Sim MR, Meyer M, Tonkin AM, Abramson MJ, Dennekamp M. Impact of fine particulate matter (PM 2.5) exposure during wildfires on cardiovascular health outcomes. *J Am Heart Assoc.* 2015;4:e001653. doi: 10.1161/JAHA.114.001653
56. Nunes KVR, Ignotti E, de Souza Hacon S. Circulatory disease mortality rates in the elderly and exposure to PM2. 5 generated by biomass burning in the Brazilian Amazon in 2005. *Cad Saude Publica.* 2013;29:589–598. doi: 10.1590/s0102-311x2013000300016
57. Shah AS, Langrish JP, Nair H, McAllister DA, Hunter AL, Donaldson K, Newby DE, Mills NL. Global association of air pollution and heart failure: a systematic review and meta-analysis. *Lancet.* 2013;382:1039–1048. doi: 10.1016/S0140-6736(13)60898-3
58. Al-Kindi SG, Sarode A, Zullo M, Brook J, Burnett R, Oliveira GH, Huang W, Brook R, Rajagopalan S. Ambient air pollution and mortality after cardiac

transplantation. *J Am Coll Cardiol.* 2019;74:3026–3035. doi: 10.1016/j.jacc.2019.09.066
59. Huynh QL, Blizzard CL, Marwick TH, Negishi K. Association of ambient particulate matter with heart failure incidence and all-cause readmissions in Tasmania: an observational study. *BMJ Open.* 2018;8:e021798. doi: 10.1136/bmjopen-2018-021798
60. Larkin S, Illson S, Evans R, Lahm P, Barkjohn K. Fire and Smoke Map. Environmental Protection Agency (2021). Accessed June 8, 2021. https://fire.airnow.gov/
61. United States Forest Service. BlueSky Daily Runs. 2021. Accessed August 14, 2021. https://tools.airfire.org/websky/v2/#viewer
62. National Interagency Fire Center. National Significant Wildland Fire Potential Outlook. 2021. Accessed June 8, 2021. https://www.predictiveservices.nifc.gov/outlooks/outlooks.htm
63. European Commission. Global Fire Monitoring. 2021. Accessed December 10, 2021. https://atmosphere.copernicus.eu/global-fire-monitoring
64. Environmental Protection Agency. AirNow Air Quality Notifications. 2021. Accessed June 8, 2021. www.enviroflash.info
65. Environmental Protection Agency. EPA AirNow App. 2021. Accessed June 8, 2021. https://www.airnow.gov/airnow-mobile-app/
66. Environmental Protection Agency. Smoke-Ready Toolbox. 2021. Accessed August 1, 2021. https://www.epa.gov/smoke-ready-toolbox-wildfires
67. Cascio W, Stone SL, Sacks J, Brown JS, Wildermann E. Particulate Pollution and Your Patients' Health. Environmental Protection Agency (2021). Accessed June 8, 2021. https://www.epa.gov/pmcourse
68. Environmental Protection Agency. Wildfires and Indoor Air Quality. 2021. Accessed June 8, 2021. https://www.epa.gov/indoor-air-quality-iaq/wildfires-and-indoor-air-quality-iaq
69. Javins T, Clune A, Cooper R, Emmerich S, Gallagher M, Hammond D, Henerson S, Katz S, Kosmal A, Nilsson G, et al. Planning Framework for Protecting Commercial Building Occupants from Smoke During Wildfire Events. American Society of Heating, Refrigerating and Air-Conditioning Engineers (2021). Accessed August 14, 2021. https://www.ashrae.org/file%20library/technical%20resources/covid-19/guidance-for-commercial-building-occupants-from-smoke-during-wildfire-events.pdf
70. Davies IP, Haugo RD, Robertson JC, Levin PS. The unequal vulnerability of communities of color to wildfire. *PLoS One.* 2018;13:e0205825. doi: 10.1371/journal.pone.0205825
71. Afrin S, Garcia-Menendez F. Potential impacts of prescribed fire smoke on public health and socially vulnerable populations in a Southeastern US state. *Sci Total Environ.* 2021;794:148712. doi: 10.1016/j.scitotenv.2021.148712
72. World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. 2021. Accessed September 30, 2021. https://apps.who.int/iris/handle/10665/345329
73. Michie S, Van Stralen MM, West R. The behaviour change wheel: a new method for characterising and designing behaviour change interventions. *Implement Sci.* 2011;6:1–12. doi: 10.1186/1748-5908-6-42
74. Fisk WJ, Chan WR. Effectiveness and cost of reducing particle-related mortality with particle filtration. *Indoor Air.* 2017;27:909–920. doi: 10.1111/ina.12371
75. Rajagopalan P, Goodman N. Improving the indoor air quality of residential buildings during bushfire smoke events. *Climate.* 2021;9:32. doi: 10.3390/cli9020032
76. Newman JD, Bhatt DL, Rajagopalan S, Balmes JR, Brauer M, Breysse PN, Brown AG, Carnethon MR, Cascio WE, Collman GW. Cardiopulmonary impact of particulate air pollution in high-risk populations: JACC State-of-the-Art Review. *J Am Coll Cardiol.* 2020;76:2878–2894. doi: 10.1016/j.jacc.2020.10.020
77. Janssen NA, Schwartz J, Zanobetti A, Suh HH. Air conditioning and source-specific particles as modifiers of the effect of PM (10) on hospital admissions for heart and lung disease. *Environ Health Perspect.* 2002;110:43–49. doi: 10.1289/ehp.0211043
78. Barn PK, Elliott CT, Allen RW, Kosatsky T, Rideout K, Henderson SB. Portable air cleaners should be at the forefront of the public health response to landscape fire smoke. *Environ Health.* 2016;15:1–8. doi: 10.1186/s12940-016-0198-9
79. Stauffer DA, Autenrieth DA, Hart JF, Capoccia S. Control of wildfire-sourced PM2. 5 in an office setting using a commercially available portable air cleaner. *J Occup Environ Hyg.* 2020;17:109–120. doi: 10.1080/15459624.2020.1722314
80. Walzer D, Gordon T, Thorpe L, Thurston G, Xia Y, Zhong H, Roberts TR, Hochman JS, Newman JD. Effects of home particulate air filtration on blood pressure: a systematic review. *Hypertension.* 2020;76:44–50. doi: 10.1161/HYPERTENSIONAHA.119.14456
81. Association of Home Appliance Manufacturers (AHAM). Frequently Asked Questions About Testing of Portable Air Cleaners. 2020. Accessed August 1, 2021. https://ahamverifide.org/wp-content/uploads/2020/09/Testing-of-Portable-Air-Cleaner-Performance-FAQs-2020-Updates.pdf
82. Koenigshofer PE, Murphy J, Walter Grondzik PE, Brown R, Burroughs D, Connell J, Corin H, Crozier J, Fauber J, Hanegan T, et al. HVAC Design Manual for Hospitals and Clinics (Second Edition). American Society of Heating, Refrigerating and Air-Conditioning Engineers (2021). Accessed September 30, 2021. https://www.ashrae.org/technical-resources/bookstore/hvac-design-manual-for-hospitals-and-clinics
83. Nguyen PD, Martinussen N, Mallach G, Ebrahimi G, Jones K, Zimmerman N, Henderson SB. Using low-cost sensors to assess fine particulate matter infiltration (PM2. 5) during a wildfire smoke episode at a large inpatient healthcare facility. *Int J Environ Res Public Health.* 2021;18:9811. doi: 10.3390/ijerph18189811
84. Konda A, Prakash A, Moss GA, Schmoldt M, Grant GD, Guha S. Aerosol filtration efficiency of common fabrics used in respiratory cloth masks. *ACS Nano.* 2020;14:6339–6347. doi: 10.1021/acsnano.0c03252
85. Langrish JP, Li X, Wang S, Lee MM, Barnes GD, Miller MR, Cassee FR, Boon NA, Donaldson K, Li J. Reducing personal exposure to particulate air pollution improves cardiovascular health in patients with coronary heart disease. *Environ Health Perspect.* 2012;120:367–372. doi: 10.1289/ehp.1103898
86. Tartakovsky L, Baibikov V, Czerwinski J, Gutman M, Kasper M, Popescu D, Veinblat M, Zvirin Y. In-vehicle particle air pollution and its mitigation. *Atmos Environ.* 2013;64:320–328. doi: 10.1016/j.atmosenv.2012.10.003
87. Yu N, Shu S, Lin Y, She J, Ip HSS, Qiu X, Zhu Y. High efficiency cabin air filter in vehicles reduces drivers' roadway particulate matter exposures and associated lipid peroxidation. *PLoS One.* 2017;12:e0188498. doi: 10.1371/journal.pone.0188498
88. Chuang H-C, Lin L-Y, Hsu Y-W, Ma C-M, Chuang K-J. In-car particles and cardiovascular health: an air conditioning-based intervention study. *Sci Total Environ.* 2013;452:309–313. doi: 10.1016/j.scitotenv.2013.02.097
89. Lee ES, Zhu Y. Application of a high-efficiency cabin air filter for simultaneous mitigation of ultrafine particle and carbon dioxide exposures inside passenger vehicles. *Environ Sci Technol.* 2014;48:2328–2335. doi: 10.1021/es404952q
90. Wen , XJ, Balluz, L, Mokdad A. Association between media alerts of air quality index and change of outdoor activity among adult asthma in six states, BRFSS, 2005. *J Commun Health.* 2009;34:40–46. doi: 10.1007/s10900-008-9126-4
91. National Weather Service. Fire Weather. 2021. Accessed June 8, 2021. https://www.weather.gov/fire/
92. Environmental Protection Agency. AirNow Air Quality Notifications. 2021. Accessed June 8, 2021. https://www.enviroflash.info
93. Johnston F, Jones P, Wheeler A, Campbell S, Lucani C, Williamson G, Bowman D, Haberle S, Workman A, Koolhof I, et al. AirRater Application. AirRater (2021). Accessed August 5, 2021. https://airrater.org
94. Environmental Protection Agency. Smoke Sense Study: A Citizen Science Project Using a Mobile App. 2019. Accessed August 1, 2021. https://www.epa.gov/air-research/smoke-sense-study-citizen-science-project-using-mobile-app
95. PurpleAir. PurpleAir Map. 2021. Accessed August 18, 2021. https://map.purpleair.com
96. Yu J, Castellani K, Forysinski K, Gustafson P, Lu J, Peterson E, Tran M, Yao A, Zhao J, Brauer M. Geospatial indicators of exposure, sensitivity, and adaptive capacity to assess neighbourhood variation in vulnerability to climate change-related health hazards. *Environ Health.* 2021;20:1–20. doi: 10.1186/s12940-021-00708-z
97. Centers for Disease Control and Prevention. CDC Social Media Tools, Guidelines & Best Practices. 2021. Accessed June 8, 2021. https://www.cdc.gov/socialmedia/tools/guidelines/socialmediatoolkit.html
98. Johnston FH, Henderson SB, Chen Y, Randerson JT, Marlier M, DeFries RS, Kinney P, Bowman DM, Brauer M. Estimated global mortality attributable to smoke from landscape fires. *Environ Health Perspect.* 2012;120:695–701. doi: 10.1289/ehp.1104422
99. DeMocker J, et al. The Benefits and Costs of the Clean Air Act From 1990 to 2020, Final Report – Rev. A. Environmental Protection Agency Office of Air and Radiation (2011). Accessed December 1, 2021. https://www.epa.gov/sites/production/files/2015-07/documents/fullreport_rev_a.pdf
100. Clark ML, Peel JL, Balakrishnan K, Breysse PN, Chillrud SN, Naeher LP, Rodes CE, Vette AF, Balbus JM. Health and household air pollution from solid fuel use: the need for improved exposure assessment. *Environ Health Perspect.* 2013;121:1120–1128. doi: 10.1289/ehp.1206429